

Detection of dark energy near the Local Group with the *Hubble Space Telescope*

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We report the detection of dark energy near the Milky Way made with precision observations of the local Hubble flow of expansion. We estimate the local density of dark energy and find that it is near, if not exactly equal to, the global dark energy density. The result is independent of, compatible with, and complementary to the horizon-scale observations in which dark energy was first discovered. Together with the cosmological concordance data, our result forms direct observational evidence for the Einstein antigravity as a universal phenomenon – in the same sense as the Newtonian universal gravity.

Dark energy is the mysterious form of cosmic energy that produces antigravity and accelerates the global expansion of the universe. It was first discovered (1,2) in 1998-99 in observations of the Hubble expansion flow with the use of type Ia supernovae at horizon-size distances of more than 1000 megaparsec (Mpc) (1 Mpc is equal to 3.26 million light-years). These and other studies, especially the

observations of the cosmic microwave background (CMB) anisotropy (3,4), indicate that the global dark energy density is $(0.75 \pm 0.05) \times 10^{-26}$ kilograms per cubic meter (kg/m^3). It contributes nearly 3/4 the total energy of the universe (1-4). According to the simplest, straightforward and quite likely interpretation, dark energy is described by the Einstein cosmological constant. If this is so, dark energy is the energy of the cosmic vacuum (5) with the equation of state $p_V = -\rho_V$. Here ρ_V, p_V are the dark energy density and pressure which are both constant in time and uniform in space (the speed of light $c = 1$ hereafter). The interpretation implies that although dark energy betrayed its existence through its effect on the universe as a whole, it exists everywhere in space with the same density and pressure. How to examine this in direct observations on smaller spatial scales?

We have searched for dark energy in our closest galactic neighborhood. The local space volume is dominated by our Milky Way and its sister galaxy, M31, located at about 0.7 Mpc from us, moving toward each other with a relative velocity ~ 100 km/s. Together with the Magellanic Clouds, the Triangulum galaxy and about four dozen other dwarf galaxies, these two major galaxies form the Local Group. Around the group, two dozen dwarf galaxies are seen which all move apart of the group. This is the local expansion flow discovered in the late 1920s by Hubble.

Systematic observations of distances and motions of galaxies in the Local Group and in the flow around it have been carried out over the last eight years with the *Hubble Space Telescope* during more than 200 orbital periods (6-12). High precision measurements were made of the radial velocities (with 1-2 km/s accuracy) and distances (8-10 % accuracy) for about 200 galaxies of the Local Group and neighbors from 0 to 7 Mpc from the group barycenter.

We have focused on the shortest distances less than 3 Mpc from the Local Group barycenter. This is the very beginning of the Hubble flow of expansion. The flow is represented in Fig.1 by the plot of radial velocities versus distance, and this

is the most complete version of the Hubble diagram for these scales up to date. The velocities and distances are given in the reference frame of the barycenter of the Local Group. At less than 1 Mpc, one sees the internal, gravitationally-dominated motions of galaxies within the group. Most of the galaxies are gathered in two families around the major members of the group. The total mass of the group is estimated as $M = 1.3 \pm 0.3 \times 10^{12} M_{\odot}$ (10).

It is seen from Fig.1 that the expansion flow takes over at a distance $\simeq 1$ Mpc, just at the outskirts of the Local Group. A linear velocity-distance trend, $V \propto R$, known as the Hubble law, emerges at about 2 Mpc distance. The measured value of the local expansion rate (the Hubble parameter) is $H_0 = 72 \pm 6$ km/s/Mpc (11). The flow is rather regular and “cool”: its radial one-dimensional velocity dispersion is remarkably low, 17 km/s (9).

Like in the largest-scale studies (1,2), we use the observed expansion flow as a natural tool for probing dark energy. The dwarf galaxies of the flow are good “test particles” which may reveal for us the dynamics behind the observed flow motion. Each particle is affected by the gravitational attraction of the Local Group. Considering only the most important dynamical factors, we may take the gravity field of the group as nearly centrally-symmetric and static; this is a good approximation to reality, as exact computer simulations prove (13,14). According to Newtonian gravity law, this force gives a particle acceleration (force per unit mass)

$$F_N = -GM/R^2, \quad (1)$$

at its distance R from the group barycenter.

We consider a picture in which the Local Group and the expansion flow around it are all embedded in the dark energy with a uniform local density $\bar{\rho}_V$ which is, generally, not necessarily equal to the global density ρ_V . Respectively, each particle of the flow is also affected by the repulsive antigravity force produced by the local dark energy background. This force can be described in terms of Newtonian

mechanics as well, and according to the ‘Einstein antigravity law’, the dark energy gives acceleration

$$F_E = G2\bar{\rho}_V(\frac{4\pi}{3}R^3)/R^2 = \frac{8\pi}{3}G\rho_V R, \quad (2)$$

where $-2\bar{\rho}_V = \bar{\rho}_V + 3\bar{p}_V$ is the local effective (General Relativity) gravitating density of dark energy (for details see (15) where a General Relativity treatment is also given). The local pressure of dark energy is negative, \bar{p}_V , and so the effective gravitating density is negative as well. Because of this the acceleration is positive, and it speeds up the particle motion apart from the center.

It is seen from Eqs.1 and 2 that the gravity force ($\propto 1/R^2$) dominates over the antigravity force ($\propto R$) at small distances, and here the total acceleration is negative. At large distances, antigravity dominates, and the acceleration is positive there. Gravity and antigravity balance each other, and so the acceleration is zero, at the “zero-gravity surface” which has a radius

$$R_V = (\frac{3M}{8\pi\bar{\rho}_V})^{1/3}. \quad (3)$$

If one takes into account the real structure of the Local Group, it may be seen (13,14) that the zero-gravity surface is not exactly spherical and not exactly static; but it is nearly spherical and remains almost unchanged (within the 15-20% accuracy) since the formation of the Local group some 12 Gyr ago, as the computer simulations indicate.

The model described by Eqs.1-3 is obviously very different from the Friedmann cosmological model of a uniform and isotropic universe. And this must be so, because there is no uniformity or isotropy on the spatial scale of a few Mpc. Moreover, the force field of the universe as a whole is non-stationary and changing with time, while the local force field (given by Eqs.1-2) is static. Consequently, the motion of the local flow galaxies hardly originated in the global initial isotropic Big Bang; its nature is rather essentially local and caused by the local processes. One may imagine that the flow galaxies gained their initial velocities in the early

days of the Local Group when its major and minor galaxies participated in violent non-linear dynamics with multiple collisions and mergers. In this process, some of dwarf galaxies managed to escape from the gravitational pool of the Local Group after having gained escape velocity from the non-stationary gravity field of the forming group. This process is suggested by the concept of the “Little Bang”(16) and supported by the computer simulations (13,14).

When escaped particles occur beyond the zero-gravity surface ($R > R_V$), their motion is controlled mainly by the dark energy antigravity. The general trend of the dynamical evolution of the flow may be seen from Eqs.1-3. At large enough distances where antigravity dominates over gravity almost completely, the velocities of the flow are accelerated and finally they grow with time exponentially: $V \propto \exp[H_V t]$. At this limit, the distances grow exponentially as well. As a result, the expansion flow acquires the linear velocity-distance relation asymptotically: $V \rightarrow H_V R$. Here the value

$$H_V = \left(\frac{8\pi G}{3}\bar{\rho}_V\right)^{1/2} \quad (4)$$

is the expansion rate which is constant and determined by the local dark energy density alone.

The zero-gravity radius R_V is obviously the key physical quantity in this picture. How to find its value in the observed expansion flow? Basing on the dynamics considerations above, we may robustly restrict the value of R_V with the use of the diagram of Fig.1. Indeed, since the zero-gravity surface lies outside the Local Group volume, it should be that $R_V > 1$ Mpc. On the other hand, the fact that the linear velocity-distance relation is seen from a distance of about 2 Mpc suggests that $R_V < 2$ Mpc. If so, Eq.3 leads directly to the robust upper (from $R > 1$ Mpc) and lower ($R < 2$ Mpc) limits to the local dark energy density:

$$(0.1 \pm 0.03) < \bar{\rho}_V < (1 \pm 0.3) \times 10^{-26} \text{ kg/m}^3. \quad (5)$$

(Here the measured value of the Local Group mass is also used.)

The lower limit in Eq.5 is most significant. It means that the dark energy does exist in the nearby universe. In combination, both limits imply that the value of the local dark energy density is near the value of the global dark energy density, $\bar{\rho}_V \sim \rho_V$, or may be exactly equal to it. Anyway, the global figure for ρ_V ($(0.75 \pm 0.05) \times 10^{-26} \text{ kg/m}^3$ – see above) lies comfortably in the range given by Eq.5.

It seems amazing that such a fundamental physical quantity as the density of cosmic vacuum, comes from a simple combination $\bar{\rho}_V = \frac{3M}{8\pi R_V^3}$ of rather modest astronomical quantities which are the Local Group mass and the starting distance of the Hubble flow of expansion.

Thus, the observations of the local expansion flow enable us to discover local dark energy in the nearby universe and estimate its density at a distance of a few Mpc from the Milky Way galaxy. The result is completely independent of the largest-scale cosmological observations (1,2) in which dark energy was first discovered; it is also compatible with and complementary to them.

Now we discuss the result and its implications.

1. As we already mentioned, the dark energy first revealed itself in the Hubble flow at very large distances. It was found (1,2) that the global cosmological expansion was decelerated by gravity at times earlier than at the redshift $z = z_V \simeq 0.7$ (which corresponds to a distance $\sim 1000 \text{ Mpc}$) and accelerated by antigravity at times later than $z = z_V$. At the redshift $z = z_V$, the antigravity of dark energy and the gravity of matter (baryons and dark matter) balance each other for a moment. The balance condition is $\rho_M(z_V) - 2\rho_V = 0$, where $\rho_M(z)$ is the cosmological matter density. Since the matter density scales with redshift as $(1+z)^3$ and the present-day matter density is known, $\rho_M(z=0) \simeq 0.3 \times 10^{-26} \text{ kg/m}^3$, the estimate of the global dark energy density comes from the balance relation: $\rho_V = \frac{1}{2}\rho_M(z=0)(1+z_V)^3$ (see its numerical value in the beginning of the paper).

In our search for the local dark energy, we have followed exactly the same

logic. Indeed, the zero-gravity radius of Eq.3 is an exact local counterpart of the “global” redshift z_V : they both indicate the gravity-antigravity balance. But what is temporal globally proves to be spatial locally: the balance takes place only at one proper-time moment (at $z = z_V$) in the Universe as a whole, while it exists all the time since the formation of the Local Group at only one distance ($R = R_V$) from the group center. Unfortunately, the accuracy of the determination of R_V is still considerably lower than in the case of z_V ; this is mainly because of a relatively small number of galaxies – only two dozens – in the observed local flow.

The global studies (1,2) are reasonably treated as direct probe of dark energy – contrary, for instance, to implications from CMB studies (3,4) which are considered indirect. In the same sense, our local method is the direct one.

2. Our model leads to an important specific prediction. It follows from Eqs.1-3 that at distances $R > R_V$, the velocities of the local expansion flow must be not less than a minimal velocity V_{esc} . The minimal velocity comes from the minimal total mechanical energy needed for a particle to escape from the gravitational potential well of the Local Group. Actually, this prediction may serve as a critical test for the model.

In Fig.1, the minimal velocity V_{esc} is shown by a bold curve; it turns to zero at $R = R_V$ and grows nearly linearly at $R > R_V$. This is one curve of a bunch of the curves that cross the distance segment from 2.1 to 2.3 Mpc corresponding to the observed position of the galaxy I5152 on the diagram. At $R > R_V$, the bunch leaves all the 20 other galaxies above the critical curves. The bunch parameters are the mass of the Local Group M and the dark energy density $\bar{\rho}_V$, and if the mass is taken to be $M = 1.3 \pm 0.3 \times 10^{12} M_\odot$ (see above), then the local dark matter density must be

$$\bar{\rho}_V = (0.6 \pm 0.3) \times 10^{-26} \text{ kg/m}^3. \quad (6)$$

Thus, the model passes the test with these parameters, and in this way, the diagram of Fig.1 leads to a new independent estimate of the dark energy density. The value

of Eq.6 is compatible with the interval of Eq.5.

As is seen in Fig.1, the velocity-distance structure of the flow follows the trend of the minimal velocity: the linear regression line of the flow (the thin line) is nearly parallel to the minimal velocity curve, at $R > R_V$.

A stronger condition may also be checked which requires that all the 21 galaxies at $R > R_V$ (including the galaxy I5152) are above the critical lines. In this case, the value of Eq.6 gives an upper limit for the local dark energy density.

Note that the test is rather sensible: for instance, with a higher value of the local dark energy density, say, $1.5 \times 10^{-26} \text{ kg/m}^3$, over half of the galaxies would lie below the curve of the minimal velocity.

For a comparison, a similar minimal escape velocity is shown also for a “no-vacuum model” with zero dark energy density – dashed line in Fig.1. The real flow ignores obviously the trend of the minimal velocity in this case: the velocities of the flow grow with distance, while the minimal velocity decreases. It is seen also that two galaxies of the flow violate obviously the no-vacuum model: they are located below the dashed line. This comparison is clearly in favor of the vacuum energy model and against the model with no dark energy.

3. Another independent test of the model involves the measured value of the local expansion rate $H = 72 \pm 6 \text{ km/s/Mpc}$ (11). Indeed, the model predicts that the expansion rate must be near the value of H_V (see Eq.4), at distances larger than, say, 2 Mpc. So putting roughly $H = H_V$, we get from this equality a new estimate for the local dark energy density:

$$\bar{\rho}_V = \frac{3}{8\pi G} H^2 = (1 \pm 0.2) \times 10^{-26} \text{ kg/m}^3. \quad (7)$$

The result is compatible with Eqs.5,6, hence the model passes this test as well.

Interesting enough, the three seemingly unrelated quantities – the Local Group mass M , the starting distance of the expansion flow R_V and the expansion rate H – prove to be essentially linked, so that $H^2 R_V^3 / (GM) \sim 1$. In this fact, the self-consistency of the model manifests itself.

4. According to recent studies by Sandage and his colleagues (see a summarizing paper (17) and references therein), a regular Hubble flow of expansion is observed over a very large distance range from 4 to 200 Mpc. The flow exhibits the Hubble velocity-distance law, and its expansion rate $H_0 = 62.3 \pm 6.3$ km/s/Mpc is practically the same over the whole scale range. The simple model of Eqs.1-5 cannot be applied in this case directly. But our dynamics analysis above (see also papers (18-21)) suggests that the kinematic regularity of the flow is possible only due to the smoothing effect of the perfectly uniform dark energy on the otherwise lumpy gravitational force field of the chaotic and non-uniform distribution of the galaxies. In this case, the rate of expansion must be near the universal value H_V of Eq.4.

With this new understanding, the data (17) may be used to estimate the local dark energy density on the scales 4-200 Mpc. Using the equality $H_0 = H_V$, we have:

$$\bar{\rho}_V = \frac{3}{8\pi G} H_0^2 \simeq (0.74 \pm 0.2) \times 10^{-26} \text{ kg/m}^3. \quad (8)$$

This value is practically equal to the global dark energy density ρ_V .

5. Beyond the Local Group's neighboring expanding population which we examined here, small galaxy groups have long been known to be quite common; recent studies demonstrate this definitely (22,23). Computer identified groups from observational galaxy catalogs (24) have been shown to have an expanding population via a Doppler shift number asymmetry relative to the brightest member. Large N-body Λ CDM cosmological simulations (25-28) show that a structure with a massive group in its center and a cool expansion outflow outside is rather typical for scales of a few Mpc and more. The relative numbers of simulated groups of different kinds (29) are near the observed ones, if the local dark energy density is assumed at the level of Eq.8. Such studies of other galaxy groups complement usefully our approach to the dark energy detection around the Local Group.

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Figure caption

Fig.1. The Hubble diagram for the very local (distance $R < 3$ Mpc) universe based on *A catalog of Neighboring Galaxies* (12). The galaxies of the Local Group are located within the area of 1 Mpc across. The flow of expansion starts in the outskirts of the group and reveals the linear velocity-distance relation (the Hubble law) at $R \geq 2$ Mpc (see also the text).

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